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FINAL TECHNICAL REPORT

TURBULENCE MODELING/TRAINING

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ITHACA, NY 14853

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13. ABSTRACT *(Maximum 200 words)*

Beginning with the code flo103 of Jameson and Martinelli, a robust, flexible numberical platform has been constructed which can accept O and R meshes as well as C, accepts a variable number of PDEs in the turbulence models, has consistent gradient compensation, enhanced multi-grid sequencing, a restart option, various post-processing options, the option of recording convergence histories, accepts K-e, k-e-S, second order and Baldwin-Lomax turbulencemodels, has dynamical memory allocation, vectorized data structure and Unix integration, and computes subsonic, transonic and supersonic flows. Virtually any turbulence model can be run in essentially any two-dimensional geometry, so that they can be compared on an equal footing. The following cases have been computed: homogeneous grid turbulence; plane jet and mixing layer; flat pllate boundary layers; semi-infinite plate (subonic (Clauser) and supersonic (Delery)); finite plate (subsonic (ONERA)); supersonic compression ramp (Settles et al - Mach 2.93); Delery bump.

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2. Objectives.

To develop computational turbulence models of various sorts, and a numerical platform, so as to compute turbulent flows of all sorts in various geometries.

3. Abstract of progress.

Beginning with the code flo103 of Jameson and Martinelli, a robust, flexible numerical platform has been constructed which can accept O and R meshes as well as C, accepts a variable number of PDEs in the turbulence models, has consistent gradient compensation, enhanced multi-grid sequencing, a restart option, various post-processing options, the option of recording convergence histories, accepts k-ε, k-ε-S, second order and Baldwin-Lomax turbulence models, has dynamical memory allocation, vectorized data structure and Unix integration, and computes subsonic, transonic and supersonic flows. Virtually any turbulence model can be run in essentially any two-dimensional geometry, so that they can be compared on an equal footing. The following cases have been computed: homogeneous grid turbulence; plane jet and mixing layer; flat plate boundary layers; semi-infinite plate (subsonic (Clauser) and supersonic (Delery)); finite plate (subsonic (ONERA)); supersonic compression ramp (Settles et al - Mach 2.93); Delery bump. Documentation is in preparation.

4. Summary of accomplishments.

The progress described in 3. (above) will make possible the comparison on an equal footing of virtually any turbulence model in nearly any two-dimensional geometry in flows with widely varying parameters. We have already compared the performance of a number of standard models in a variety of situations. In addition, we have devised some new models for the transonic and supersonic flows, and will be comparing those. A program of this sort was recommended in late 1995 by an all-industry panel convened by Joe Marvin at NASA Ames; specifically, the panel recommended that any proposed new model be subjected to this type of testing in a wide variety of flows (parameters and geometries) on a single platform, and compared with existing models, before being submitted to the industry for use. Our investigation predated the panel recommendation by three years. To the best of our knowledge, our numerical platform is the only one sufficiently flexible to compute the range of parameters, geometries and turbulence models required. We found in developing the numerical platform that existing platforms often had

undesirable interactions between, for example, mesh refinement or convergence acceleration, and turbulence model type so that results were biased.

In parallel efforts, we have been exploring other types of models for turbulent flows, specifically models which resolve only the coherent structures, parameterizing the smaller-scale, more disorganized turbulence. Such models are useful, for example, in simulating panel vibration, sonar self-noise, turbine blade heat transfer and so forth.

5. List of Personnel:

Faculty: J. L. Lumley (Cornell, PI); G.Berkooz (Cornell/BEAM Technologies); S. Leibovich (Cornell); N. Aubry (CCNY; NJTI); I. Moroz (Oxford).

Post-doctoral associates: H. Carlson

Students: J. Gibson.

6. Publications during the report period.

173. Berkooz, G., Holmes, P., Aubry, N., Lumley, J. L. & Stone, E. 1994. Observations regarding "Coherence and chaos in a model of the turbulent boundary layer"(by X. Zhou & L. Sirovich). *Physics of Fluids*, 6: 1574-1578.

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179. Lumley, J. L. 1994. Technical Evaluation Report, in *Application of Direct and Large Eddy Simulation to Transition and Turbulence.* AGARD-CP-551. pp. T-1-T-4. NATO: AGARD.

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184. Bradshaw, P., Launder, B. E. & Lumley, J. L. 1996. Collaborative testing of turbulence models. *J. Fluids Engineering*, 118:243-247.

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186. Holmes, P. J., Lumley, J. L and Berkooz, G. 1996. *Turbulence, Coherent Structures, Dynamical Systems and Symmetry*. Cambridge, UK: University Press.

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188. Shih, T.-H. & Lumley, J. L. 1995. Applications of direct numerical simulation of turbulence in second order closures. NASA Contractor Report 198386 (ICOMP-95-13; CMOTT-95-2). Lewis Research Center.

189. Carlson, H. A., Berkooz, G. and Lumley, J. L. 1995. Direct numerical simulation of flow in a channel with complex, time-dependent wall geometries: a pseudospectral method. *J. Comp. Physics* 121: 155-175.

190. Carlson, H. A. and Lumley, J. L. 1996. Flow over an obstacle emerging from the wall of a channel. *AIAA J.* 34(5):924-931.

191. Carlson, H. A. and Lumley, J. L. 1996. Active control in the turbulent boundary layer of a minimal flow unit. *J. Fluid Mechanics.* In press.

192. Lumley, J. L. & Podvin, B. 1996. Dynamical Systems Theory and Extra Rates of Strain in Turbulent Flows. *J. Exp. & Therm. Fluid Sci.* 13:180-189.

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201. Podvin, B. & Lumley, J. L. 1998. Reconstructing the flow in the wall region from wall sensors. *The Physics of Fluids* 10(5):1182-1190.

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7. Interactions / Transitions.

We are interacting actively with T.-H. Shih of CMOTT at NASA Lewis and G. Berkooz, of BEAM Technologies Inc., as well as with Irene Moroz of Oxford University (UK) and Dietmar Rempfer of the University of Stuttgart (Germany) (who is spending three years with us). In collaboration with these personnel, we are developing various turbulence models which we anticipate will ultimately be helpful in predicting stage losses and heat transfer in compressor and turbine blade passages in axial flow turbomachines.

8. New discoveries, inventions, patent disclosures, etc.

None.

9. Honors / Awards

a) During this grant period:

Fellow, AIAA
Dryden Lectureship in Research

b) Lifetime achievement honors:

Haute Distinction Honoris Causa - Ecole Central de Lyon, 1987.
Fellow, American Academy of Arts and Sciences.
Member, National Academy of Engineering.
Timoshenko Medal, American Society of Mechanical Engineers, 1993
AIAA Fluid and Plasmadynamics Award, 1982.
APS Fluid Dynamics Prize, 1990.
Dryden Research Lectureship, AIAA.
Fellow, APS.
Fellow, AIAA.